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MINIMUM WETTING RATE OF A VERTICAL SURFACE IN A TWO-PHASE LIQUID-GAS FLOW IN A FIELD OF CENTRIFUGAL FORCES. I. ANALYSIS OF THE PROCESS FOR COUNTERCURRENT FLOW

by

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Minimum Wetting Rate of a Vertical Surface in a Two-Phase Liquid-Gas Flow in a Field of Centrifugal Forces. I. Analysis of the Process for Countercurrent Flow

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As a result of considerations the following equation is given:

$$Re_{\min} = \left(\frac{3D + n^4 C Re_{\min}^{4/3} - n^3 K Re_{\min}^{2/3}}{2n^5 A} \right)^{3/5}.$$

describing the values of the minimum wetting Reynolds number Re_{min} related to the wetting of the inner surface of a vertical pipe in a countercurrent two-phase liquid-gas flow in the field of centrifugal forces. The value of the coefficient n taking into account the deviation between the theoretical Reynolds numbers Re_{mint} and the experimental ones Re_{min} should be determined experimentally.

Moreover, it has been found that the rotational motion of the wetting surface brings about a decrease in the values Re_{min} in comparison with the Reynolds numbers Re^0_{min} which are indispensable for covering the whole wetting surface in the case of the absence of rotation.

1. INTRODUCTION

The problem of minimum unit wetting rate has been considered in a series

of studies both in a theoretical and experimental way.

By this concept the minimum unit wetting rate defines such a wetting value under which the whole covering of the wetting surface by a flowing liquid does not occur.

From the theoretical considerations presented in research work [1] it follows that the value of the minimum wetting rate Γ_{min} in the case when the gas phase is immobile, is decided, among others, by the centrifugal acceleration a.

This study is a continuation of the investigations on minimum wetting rate Γ^0_{min} in a two-phase flow and in particular refers to the minimum wetting rate Γ_{min} of the inner surface of a vertical pipe in a countercurrent two-phase liquid-gas flow in the field of centrifugal forces.

In this work the process in which the flowing liquid wets the inner surface of the vertical pipe while the gas flows from the bottom toward the top by the remaining section of the pipe is called the countercurrent two-phase liquid-gas flow.

The dependence Γ_{min}, and more strictly corresponding to it, the Reynolds numbers Re_{min} were formulated from the following quantities: centrifugal acceleration a, absolute value of gas in w_g extreme angle of wetting θ and physical properties of density ρ and viscosity η fluids. Results of the theoretical considerations

made it possible to establish the effect of centrifugal acceleration a on the minimum values of Reynolds numbers Re_{min}.

2. THEORETICAL MINIMUM WETTING RATES Γ_{mint}

According to Hobler [1] the total kinetic energy e_k corresponding to the velocity of the liquid layer in a vertical direction and of the energy e_σ of tensions at the interfacial surface decides the minimum value of the unit wetting rate Γ^*_{mint}, in the case when the gas phase is immobile.

In this work it is given that the Γ_{mint} value is also decided by the total of the unit of kinetic energy e_k, corresponding to the velocity of the liquid layer in a vertical direction in a countercurrent two-phase liquid-gas flow and the unit of energy e_σ resulting from the appearance of tensions at interfacial surfaces. Consequently the energy deciding the value Γ_{mint} can be presented by the following equation:

$$e = e_k + e_\sigma. \tag{1}$$

2.1 UNIT KINETIC ENERGY e_k

With attention to the small thickness of the liquid layer in relation to the inner diameter of wetted pipes used in industry [2, 3], the flow-off of liquid along the inner surface of the pipe was handled as the flow-off of liquid along the vertical flat wall [4].

In research work [4] the formula is given:

$$e_k = A\,Re_c^{5/3}x^{-2/3} + B\,Re_c - C\,Re_c^{4/3}x^{-1/3}, \tag{2}$$

where

$$A = \frac{1}{24{,}236}\,b^5 g\varrho_c\vartheta_{zc}^2, \tag{2a}$$

$$B = \frac{1}{512{,}102}\,\frac{b^3\lambda^2\varrho_g^2 w_g^4}{g\varrho_c}, \tag{2b}$$

$$C = \frac{1}{56{,}368}\,b^4\lambda\varrho_g w_g^2\vartheta_{zc}, \tag{2c}$$

$$\vartheta_{zc} = \left(\frac{\eta_c^2}{\varrho_c^2 g}\right)^{1/3},$$

describing unit kinetic energy e_k of the liquid layer flowing off along the flat vertical surface. The quantity w_g denotes the average velocity of gas counted in relation to the surface of liquid flowing off, equal to the total of liquid velocity w'_c on the surface of the layer and the absolute velocity of gas w_{gb} described by the equation

$$w_{gb} = \frac{4V}{\pi d^2}.$$

The values of coefficient b, defined as the ratio of mean thickness s of laminar layer of liquid in a countercurrent two-phase liquid-gas flow to the mean equivalent thickness s_z, are described by the equation

$$b^3 - Tb^2 - 1 = 0, \tag{3}$$

where

$$T = \frac{3}{16}\,\frac{\lambda\varrho_g w_g^2}{\varrho_c g s_z}, \tag{3a}$$

$$s_z = 0{,}9085\,\vartheta_{zc}Re_c^{1/3}, \tag{3b}$$

given in work [4].

Equations (2) and (3) are designated by the following assumption [4]:

(a) the liquid is distributed equally along the wetted surface by an ideal spray;

(b) after a starting path the liquid flow is developed, then the velocity profile in the fluid layer is stabilized;

(c) the flow-off of the liquid is laminar with the omission of surface undulation, the liquid then flows as a layer of identical thickness;

(d) the phenomenon of detachment of drops from the layer of flowing liquid does not occur;

(e) mass transfer does not occur nor does a heat transfer between the fluid and gas.

2. 2 UNIT TENSION ENERGY e_{σ}

The image of tensions at interfacial surfaces in the case of centrifugal acceleration is presented in Figure 1 [1]. Energy E_{σ} corresponding to the tensions presented is described by the following [1]

$$E_{\sigma} = F_1(\sigma_{1-2} - \tau) + F_1\sigma_{2-3} + F_2\sigma_{1-3}. \qquad (4)$$

After establishing equilibrium of forces for the given assembly solid-liquid-gas the equation [1] is fulfilled

$$\sigma_{1-3} = \sigma_{2-3}\cos\theta + \sigma_{1-2}.$$

Considering the last equation in relation to (4) we get

$$E_{\sigma} = F_1\sigma_{1-2} - F_1\tau + F_1\sigma_{2-3} + F_2(\sigma_{2-3}\cos\theta + \sigma_{1-2}). \qquad (5)$$

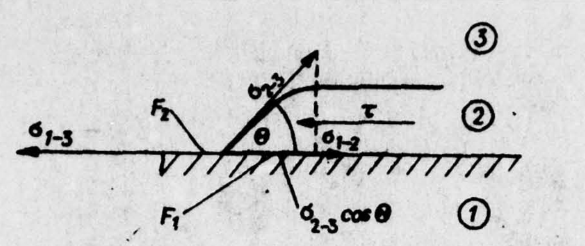

Fig. 1. Image of surface tensions at interfacial surface in the case of wetted surface rotation
1 – ciało stałe – solid, *2* – ciecz – liquid, *3* – gaz – gas

Bringing to this equation the concept: unit tension energy $e_\sigma = E_\sigma / F (J/m^2)$ and the degree of surface covering by liquid $x = F_1/F$, after simple transformations we get the equation

$$e_\sigma = Dx - x\tau + H, \tag{6}$$

where

$$D = \sigma_{2-3}(1 - \cos\theta), \quad H = \sigma_{2-3}\cos\theta + \sigma_{1-2}.$$

The quantity τ appearing equation (6) denotes the shear stress at surface being the result of the occurrance of centrifugal acceleration (Fig. 1) [1]. Then, theoretical considerations conducted by Hobler [1] lead to the following

$$\tau = \frac{\varrho c s_l^2 a}{2}, \tag{7}$$

describing the value of stress τ.

The thickness s_{l} of the laminar liquid layer is described by the equation

$$s_l = 0{,}9085\, b\, \vartheta_{sc} Re_{c,l}^{1/3} \tag{8}$$

given in work [4].

With attention to the only partial liquid covering of the wetted surface, the local Reynolds number $Re_{c,l}$ can be presented by the equation [5] :

$$Re_{c,l} = \frac{4\Gamma}{\eta_c} = \frac{4G}{x\eta_c} = \frac{1}{x} Re_c. \qquad (9)$$

The Reynolds number Re_c is calculated as if the entire surface were covered by a layer of liquid, flowing with mass rate G.

It is easy to note that when the layer of liquid covers the enti re wetted surface [redacted] evenly, then $x=1$, the value of the local Reynolds number $Re_{c,l}$ is equal to average Reynolds number Re_c.

Considering the equations (8) and (9) in equation (7) we finally get

$$\tau = 0{,}4127\, b\, \vartheta_{sc}^2 \varrho_c a Re_c^{2/3} x^{-2/3}$$

or

$$\tau = K Re_c^{2/3} x^{-2/3}, \qquad (10)$$

where

$$K = 0{,}4127\, b\, \vartheta_{sc}^2 \varrho_c a. \qquad (10a)$$

Using equation (10) with reference to (6) we may write

$$e_\sigma = Dx - K Re_c^{2/3} x^{1/3} + H. \qquad (11)$$

As already mentioned the total of the energy e_k and e_σ decides the value of Γ_{mint}. Considering equations (2) and (11) with reference to (1) the following equation is obtained

$$e = A Re_c^{5/3} x^{-2/3} + B Re_c - C Re_c^{4/3} x^{-1/3} + Dx - K Re_c^{2/3} x^{1/3} + H, \qquad (12)$$

defining the whole unit energe e.

In order to illustrate this equation Figure 2 presents the values of factors e-H for $\theta = 10^0$, $w_{gb} = 10$m/s and several Re_c, a and x.

The relative gas velocity w_g, occurring in the quantities B and C of this equation are calculated according to the equation

$$w_g = w_{gb} + w'_c,$$

where

$$w'_c = \frac{g \varrho_c s^2}{2\eta_c} - \frac{\lambda \varrho g w_g^2 s}{8\eta_c},$$

designated in research work [4].

The values for the drag coefficients λ were designated from the following relations:

(a) for laminar gas flow ($Re_{gz} < 2100$)

$$\lambda = \frac{86}{Re_{gz}};$$

(b) for turbulent gas flow ($Re_{gz} \geq 2100$)

$$\lambda = \frac{0,3441}{Re_{gz}^{0,229}},$$

where

$$Re_{gz} = \frac{w_{gz} d \varrho_g}{\eta_g}, \quad w_{gz} = w_{gb} + w_{c,z},$$

$$w_{c,s} \mp \frac{Re_c \eta_c}{4 \varrho_c s_s}, \quad d = D_1 - 2s_z,$$

given in research work [6] .

The calculation of the value e-H was made for the water-air system, whose physical properties are:

$$\varrho_c = 998{,}6\ \mathrm{kg/m^3}, \quad \varrho_g = 1{,}17\ \mathrm{kg/m^3}, \quad \eta_c = 1{,}09\cdot10^{-3}\ \mathrm{kg/ms},$$
$$\eta_g = 1{,}8\cdot10^{-5}\ \mathrm{kg/ms}, \quad \sigma = 73{,}05\cdot10^{-3}\ \mathrm{N/m}.$$

The inner diameter of the pipe $D_1 = 0.03$m was taken into calculation. The absolute air velocity w_{gb} was smaller than the velocity of the choking up of the pipe, whose values were calculated on the basis of the equations given in research work [7]. The values for coefficient b, occurring in the quantities A, B, C and K, were determined by secant method [8] according to equations (3), (3a) and (3b). Results of the calculations are graphically presented in Figure 2.

From Figure 2 which presents the equations

$$e - H = f(Re_c,\ a,\ x,\ \theta,\ w_{gb}) \quad \text{and} \quad e^0 - H = f(Re_c^0,\ x,\ \theta,\ w_{gb}),$$

it can be observed that for large values of Reynolds numbers $Re_c(Re_c^0)$, for example, larger than 100, the lowest values for the function e-H, (e^0-H), consequently the smallest value for energy e (e^0) occur when the wetted surface is completely covered (x=1). It is a different situation for small values of Reynolds numbers $Re_c(Re_c^0)$, for example smaller than 40, since the highest value of energy e (e^0) corresponds to a complete covering of the surface (x=1). It should be expected that in a range of 40 to 100 the system will aim at a tear in the liquid layer so as to result in achieving for the given case, the smallest energy value. As an example for $\theta = 10^0$ and $w_{gb} = 10$m/s the tendency for tearing of the liquid layer occurs approximately in the following Reynolds numbers:

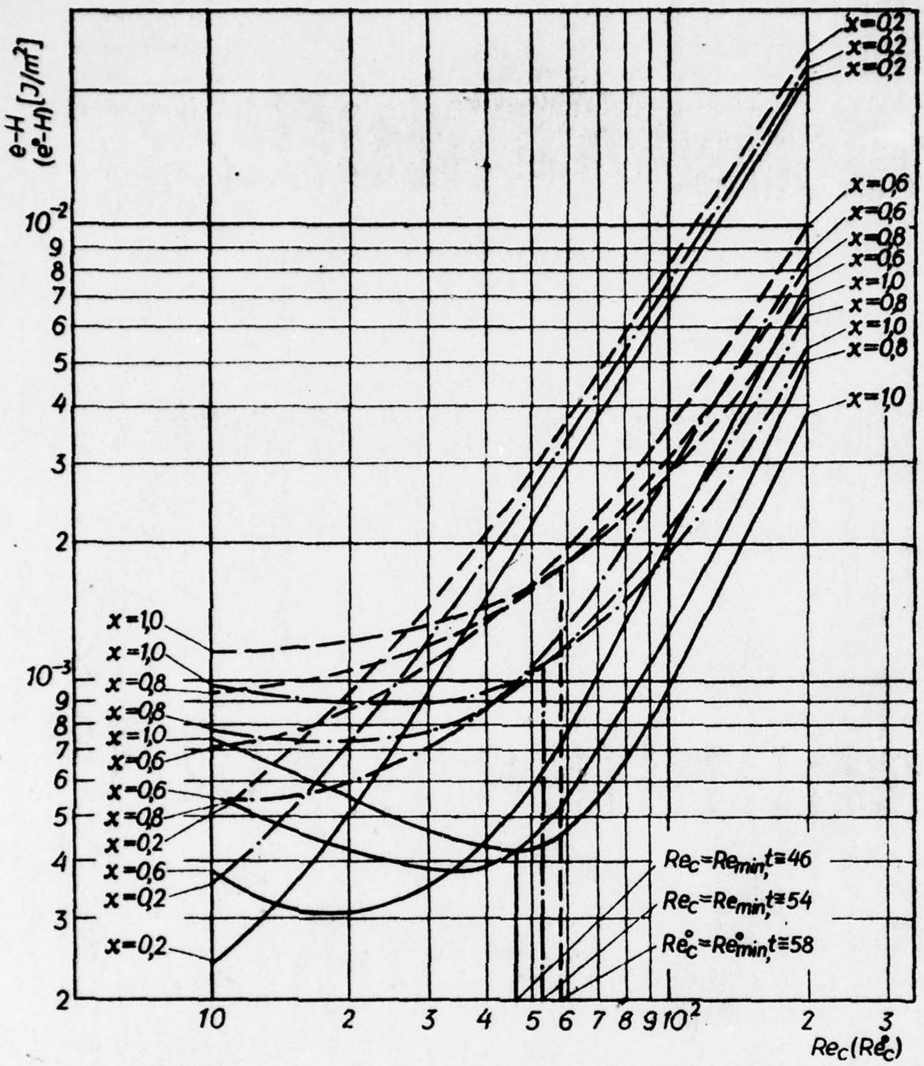

Fig. 2. Values of function $e - H$ calculated from equation (12) for $\theta = 10°$, $w_{gb} = 10$ m/s and several Re_c, x and a

- - - $a = 0$, –·–·– $a = 50$ m/s², —— $a = 100$ m/s²

$$
\begin{aligned}
a &= 0, & Re_c^0 &= Re_{mint}^0 \cong 58,\\
a &= 50\ \mathrm{m/s^2}, & Re_c &= Re_{mint} \cong 54,\\
a &= 100\ \mathrm{m/s^2}, & Re_c &= Re_{mint} \cong 46.
\end{aligned}
$$

The stretching of the liquid layer on the whole wetted surface should require an additional supply of energy. This results in the fact that the values Re_c, near which the tearing of the liquid layer can be expected, are closely connected with the centrifugal acceleration a, with unchanged values for the remaining parameters. The values $Re_c = Re_{mint}$ in the field of centrifugal forces are lower in comparison with the Reynolds numbers $Re^0_c = Re^0_{mint}$ in the case when $a = 0$. Moreover, with an increase in the value a there occurs a decrease in Reynolds numbers $Re_c = Re_{mint}$ whereby the tendency appears for the tearing of the layer of liquid previously covering the whole wetted surface.

Tearing of the layer of liquid covering the whole wetted surface can be expected when the system reaches the lowest value of energy for $0 < x \leq 1$ (5). The appearance of the [redacted] minimum of energy e defines the condition $de/dx = 0$.

The unstable condition of the liquid layer answering to the theoretical value of Reynolds number Re_{mint}, is defined by the smallest value of energy e in the case when $x = 1$. Justification of [redacted] this statement is given in research work [4].

After introducing to the derivative

$$\frac{dc}{dx} = \frac{2}{3} A\, Re_c^{5/3} x^{-8/3} + \frac{1}{3} C\, Re_c^{4/3} x^{-4/3} + D - \frac{1}{3} K\, Re_c^{2/3} x^{-2/3} = 0$$

the value [redacted] $x = 1$ and using the index mint with the Reynolds number to emphasize that it is a theoretical minimum Reynolds number value, the following equation is obtained

$$Re_{mint} = \left(\frac{3D + C\, Re_{mint}^{4/3} - K\, Re_{mint}^{2/3}}{2A} \right)^{3/5}. \qquad (13)$$

In the case where there is no centrifugal force, consequently when $a = 0$, the quantity $K = 0$ and equation (13) takes the form

$$Re_{mint} = \left(\frac{3D + C\, Re_{mint}^{4/3}}{2A} \right)^{3/5}, \qquad (14)$$

and thus the very same as the equation defining the theoretical minimum Reynolds number Re^0_{mint} in the countercurrent two-phase liquid-gas flow designated in research work [4].

Theoretical Reynolds numbers Re_{mint} are calculated on the basis of equation (13) for a water-air system at 20°C. for several angles of wetting. θ and velocity w_{gb} are presented in Figure 3, while in Figure 4 the values $(Re^0_{mint} - Re_{mint}) / Re^0_{mint}$ are given depending on acceleration a for these same parameters.

It can be stated that the rotational movement of the wetted surface brings about a decrease in the value Re_{mint} in comparison with Reynolds numbers Re^0_{mint} necessary to cover the whole wetted surface in the case of no rotation ($a = 0$).

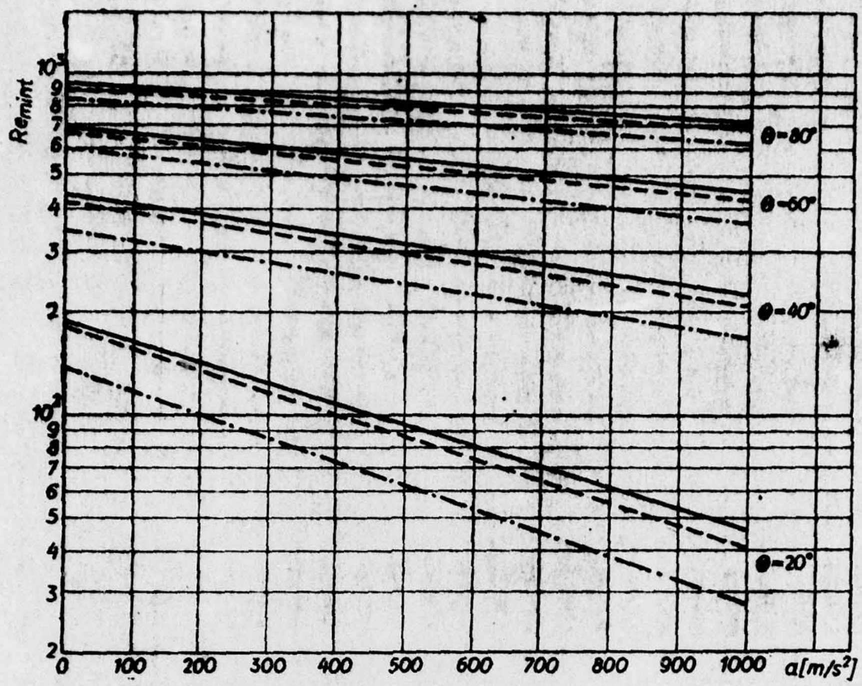

Fig. 3. Values of theoretical minimum Reynolds numbers Re_{mint} calculated from equation (13) for several angles θ and gas velocities w_{gb}

w_{gb}[m/s]: —— = 1, – – – – = 5, –.–.– = 10

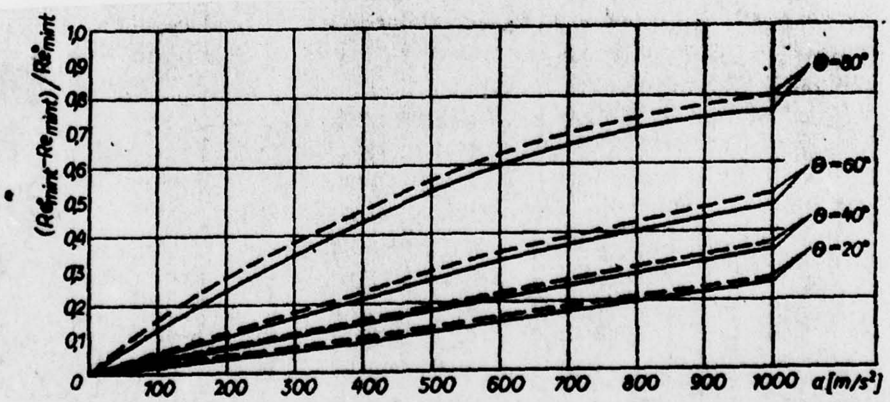

Fig. 4. Dependence of values $(Re^0_{mint} - Re_{mint})/Re^0_{mint}$ on centrifugal acceleration a, for several gas velocities w_{gb} and angles θ

w_{gb}[m/s]: —— = 5, – – – – = 10

Evident also is the strong dependence of the value Re_{mint} on the extreme angle of wetting θ and the appearance for the given acceleration a of a [redacted] larger reduction of the value Re_{mint}, in relation to Reynolds numbers Re^0_{mint}, when $a = 0$, on surfaces indicating smaller angles of wetting θ, with unchanged values for the remaining parameters. Moreover, it can be noted that with given values of θ and a, a greater reduction of value Re_{mint}, compared with Re^0_{mint}, takes place for greater gas velocities w_{gb}. Finally, Figure 5 presents a change in the value Re^0_{mint}/Re_{mint} depending on acceleration a and velocity w_{gb}.

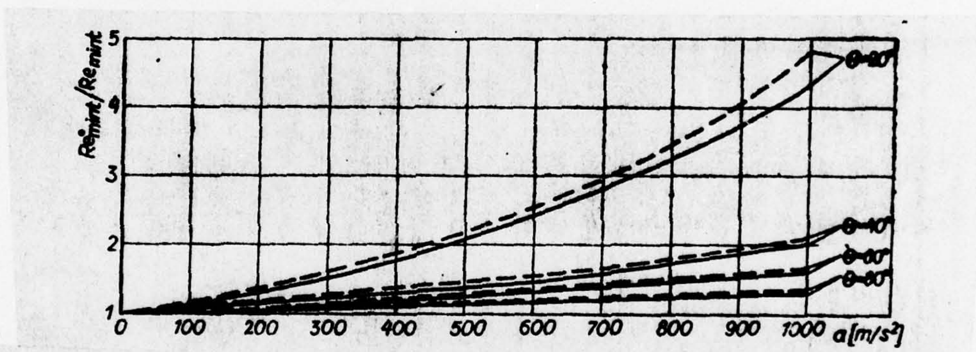

Fig. 5. Dependence of values Re^0_{mint}/Re_{mint} on centrifugal acceleration *a* for several gas velocities w_{gb} and angles θ

w_{gb} [m/s]: —— = 5, – – – = 10

It can be noted that the greatest change of the quotient Re^0_{mint}/Re_{mint} takes place with an increase in acceleration a on the surfaces indicating the smallest values of the angle of wetting θ. Moreover, it is worth noting that the values Re_{mint} can even be several times smaller than the <- Reynolds numbers Re^0_{mint}, with these same values of the remaining parameters. With greater velocities w_{gb} the values of the theoretical minimum Reynolds numbers Re_{mint} change more quickly with a change in acceleration a, when values of the remaining parameters

are unchanged (Figure 5). It is worth adding that equation (13) for $w_g = 0$ (then $C = 0$) takes the form

$$Re_{mint} = \left(\frac{3D - K\,Re_{mint}^{2/3}}{2A}\right)^{3/5}, \tag{15}$$

consequently the same as Hobler's equation defining the theoretical minimum Reynolds number Re^*_{mint} in the field of centrifugal forces in a one-phase flow, given in research work [1].

3. ACTUAL MINIMUM WETTING RATE Γ_{min}

Considerations are presented which are irrespective of the appearance of phenomena bringing about a deviation of the minimum wetting rate from the theoretical value, and the Reynolds number Re_{mint} closely corresponding to it and determined by equation (13). As was previously stated, equation (2) was determined by assuming the appearance of a uniform thickness of the wetted liquid layer. In practice, as a result of undulation in the liquid surface, irregular distribution of the liquid through sprayers, etc., the thickness of the liquid layer is not identical on the whole wetted surface.

Introducing the concept of the ratio of irregular wetting n, defined as the relation of actual thickness $s_{min,1}$ of the liquid layer at the place of its tearing to the theoretical thichness s_{min}, when wetting is ideal, then $n = s_{min,1}/s_{min}$ and using in this equation the following:

$$\delta_{min,l} = 0{,}9085\, b\, \vartheta_{sc}\, Re_{min,l}^{1/3},$$
$$\delta_{min} = 0{,}9085\, b\, \vartheta_{sc}\, Re_{min}^{1/3}$$

given in research work [4], we get

$$n = \left(\frac{Re_{min,l}}{Re_{min}}\right)^{1/3}. \qquad (17)$$

The number $Re_{min,l}$ is the local minimum Reynolds number in the thinnest place of the layer, and Re_{min} is the mean minimum Reynolds number.

The tearing of the liquid layer is the most probable in the spot where it is the thinnest. However, the value of [redacted] the local minimum Reynolds number $Re_{min,l}$ is not known, but the Re_{min} value can be determined on the basis of the known equation [2],

$$Re_{min} = \frac{4\Gamma_{min}}{\eta_c}.$$

Consequently, let us express the local minimum Reynolds number $Re_{min,l}$ by the equation

$$Re_{min,l} = n^3 Re_{min}, \qquad (18)$$

obtained from the equation (17).

Assuming that theoretical equation (13) governs each part of the layer of liquid flowing along the surface and using in that equation dependence (18), finally, we get

$$Re_{min} = \left(\frac{3D + n^4 C\, Re_{min}^{4/3} - n^2 K\, Re_{min}^{2/3}}{2n^6 A}\right)^{3/5}. \qquad (19)$$

The high exponents with the n quantity appearing in this equation indicate the very strong influence of the ratio of wetting irregularity on the values of the minimum Reynolds numbers Re_{min}.

Defining n we get $0 < n \leq 1$, then the wetting irregularity causes an increase in the value Re_{min} in comparison with the theoretical Reynolds numbers Re_{mint}.

Other phenomena also appear which bring about a deviation in the experimental results from theoretical predictions and at that, acting in the opposite direction consequently decreasing the Re_{min} values in relation to Re_{mint}. We can include in them, among others, vibration of the apparatus, undulation of the liquid layer in a vertical direction, etc. [1, 4, 9, 10].

Introducing to equation (19) additional coefficients which consider the effects which favor surface wetting, would be pointless since practically it is very difficult to isolate them. In this regard the n quantities are considerably extended, giving it a character of adjustment considering the appearance of all the phenomena bringing about the deviation of theories from practical cases.

Unfortunately the n values cannot be established theoretically but must be determined experimentally for the given liquid-gas system, with the manner used of distributing the liquid along the wetted surface [11-15].

The manner of experimental determination of the value of coefficient n is presented in research work [16]. In the cited work equations are also given which describe the n values for the wetting process of the inner surface of a vertical pipe in a countercurrent two-phase liquid-gas flow in the case of the absence of rotation of the wetted surface.

4. CONCLUSIONS

On the basis of the considerations carried out the following conclusions can be set forth:

1. The dependence Γ_{min} was formulated, and also the Reynolds numbers which closely adhere to it, from the following quantities: mean acceleration a, absolute gas velocity w_{gb}, extreme angle of wetting θ and physical properties of flows of density ρ and viscosity η, obtaining as a result of the considerations the following equation

$$Re_{mint} = \left(\frac{3D + C Re_{mint}^{4/3} - K Re_{mint}^{2/3}}{2A}\right)^{3/5},$$

which describes the values of the theoretical minimum Reynolds numbers Re_{mint} in the case of rotation of the wetted surface.

2. It was shown that the rotation of the wetted surface brings about even a several times decrease of the Re_{mint} values in comparison with Reynolds numbers Re^0_{mint} when there is no rotation. Moreover for given acceleration a, a greater

decrease in the Re_{mint} value in relation to Re^0_{mint} occurs on the surfaces indicating smaller extreme angles of wetting θ when the values of remaining parameters are unchanged.

At given values of angle θ and acceleration a, a greater decrease in Reynolds numbers Re_{mint} in comparison with Re^0_{mint} takes place for greater gas velocities w_{gb}.

3. Consideration of the deviation in theoretical values of Re_{mint} from experimental Reynolds numbers Re_{min} lead to the equation

$$Re_{min} = \left(\frac{3D + n^4 C Re_{min}^{4/3} - n^2 K Re_{min}^{2/3}}{2n^5 A}\right)^{3/5}, \qquad (20)$$

in which the quantity n takes into consideration the phenomena which bring about the deviation already mentioned.

4. Equation (20) describing the minimum Reynolds numbers Re_{min}, for the velocity of gas $w_g = 0$, takes the form

$$Re_{min} = \left(\frac{3D - n^2 K Re_{min}^{2/3}}{2n^5 A}\right)^{3/5},$$

consequently the same as Hobler's equation describing the minimum Reynolds numbers Re^*_{min} in the field of centrifugal forces in a one-phase flow.

5. Equation (20) when there is no rotation of the wetted surface is reduced to the equation

$$Re^0_{\min} = \left(\frac{3D + n^4 C (Re^0_{\min})^{4/3}}{2n^5 A} \right)^{3/5},$$

describing the values of minimum Reynolds numbers $Re^0_{\min}$ in a countercurrent two-phase liquid-gas flow without rotation of the wetted surface.

OZNACZENIA – SYMBOLS

a –	~~przyspieszenie odśrodkowe~~ centrifugal acceleration	m/s²
b –	~~stosunek średniej grubości s laminarnej warstwy cieczy w przepływie dwufazowym do średniej grubości zastępczej s_z~~ ratio of mean thickness s of laminar acceleration in two-phase flow to mean equivalent thickness s_z	
d –	~~efektywna średnica rury z uwzględnieniem zastępczej grubości warstwy cieczy spływającej~~ effective diameter of pipe taking into account equivalent thickness of liquid layer	m
D_1 –	~~wewnętrzna średnica rury zraszanej~~ inner diameter of wetted pipe	m
e –	~~energia przypadająca na jednostkę powierzchni zraszanej~~ energy corresponding to unit surface area	J/m²
e^0 –	~~energia przypadająca na jednostkę powierzchni zraszanej, gdy $a = 0$~~ energy corresponding to unit surface area, when $a = 0$	J/m²
E –	~~energia~~ energy	J
F –	~~całkowita powierzchnia zraszana~~ overall wetted surface area	m²
F_1 –	~~powierzchnia zroszona~~ wetted surface area	m²
F_2 –	~~powierzchnia niezroszona~~ not wetted surface area	m²
g –	~~przyspieszenie siły ciężkości~~ acceleration due to gravity	m/s²
G –	~~prędkość masowa cieczy~~ mass flow rate of liquid	kg/s
n –	~~współczynnik korekcyjny~~ correctional coefficient	

s – ~~średnia grubość laminarnej warstwy cieczy~~ m
mean thickness of laminar liquid layer

s_1 – ~~lokalna grubość laminarnej warstwy cieczy~~ m
local thickness of laminar liquid layer

V – ~~prędkość objętościowa gazu~~ m^3/s
volumetric flow rate of gas

w – ~~średnia prędkość liniowa~~ m/s
average linear velocity

x – ~~stopień pokrycia powierzchni cieczą~~
ratio of surface covering by liquid

Γ – ~~jednostkowe natężenie zraszania~~ kg/m·s
unit wetting rate

Γ^0 – ~~jednostkowe natężenie zraszania, gdy $a = 0$~~ kg/m·s
unit wetting rate, when $a = 0$

Γ^* – ~~jednostkowe natężenie zraszania w przepływie jednofazowym ($w_{gb} = 0$)~~ kg/m·s
unit wetting rate in one phase flow ($w_{gb} = 0$)

η – ~~lepkość dynamiczna~~ kg/m·s
dynamic viscosity

θ_z – ~~zastępczy wymiar poprzeczny liniowy dla przepływu niewymuszonego~~ m
equivalent linear dimension for free flow

θ – ~~kąt skrajny zwilżania powierzchni~~
extreme angle of wetting

λ – ~~współczynnik oporu hydraulicznego~~
drag coefficient

ϱ – ~~gęstość~~ kg/m^3
density

σ – ~~napięcie powierzchniowe~~ N/m
surface tension

τ – ~~naprężenie styczne do ściany~~ N/m
shear stress at surface

MODUŁY BEZWYMIAROWE – DIMENSIONLESS GROUPS

$Re_c = \frac{4\Gamma}{\eta_c}$ – liczba Reynoldsa cieczy
liquid Reynolds number

$Re_c^0 = \frac{4\Gamma^0}{\eta_c}$ – liczba Reynoldsa cieczy, gdy $a = 0$
liquid Reynolds number, when $a = 0$

$Re_{min} = \frac{4\Gamma_{min}}{\eta_c}$ – minimalna liczba Reynoldsa cieczy
minimum liquid Reynolds number

$Re^0_{min} = \frac{4\Gamma^0_{min}}{\eta_c}$ – minimalna liczba Reynoldsa cieczy, gdy $a = 0$
minimum liquid Reynolds number, when $a = 0$

$Re^*_{min} = \frac{4\Gamma^*_{min}}{\eta_c}$ – minimalna liczba Reynoldsa cieczy dla przepływu jednofazowego ($w_{gb} = 0$)
minimum liquid Reynolds number for one-phase liquid flow ($w_{gb} = 0$)

$Re_{gz} = \frac{w_{gz} d \varrho_g}{\eta_g}$ – zastępcza liczba Reynoldsa gazu
– equivalent gas Reynolds number

INDEKSY - INDICES

b — ~~oznacza wartość bezwzględną~~
denotes absolute value

c — ~~odnosi się do cieczy~~
refers to liquid

g — ~~odnosi się do gazu~~
refers to gas

k — ~~dotyczy wartości kinetycznych~~
refers to kinetic values

l — ~~oznacza wartości lokalne~~
denotes local values

min — ~~oznacza wartości minimalne~~
denotes minimum values

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